Detect & Avoid Alerting Logic for Unmanned Systems[1]

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NASA Langley Formal Methods work in support of the NASA UAS in the NAS Project

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[1]This working document contains information that is publicly available (see references). The DAIDALUS logo was designed by M. Malekpour.

What's in a Name?

- DAIDALUS is a reference to the craftsman of Greek mythology, *Daedalus*, the father of Icarus.

- Daedalus made wings for himself and for Icarus and warned Icarus not to fly too high, because the heat of the sun would melt the wax, nor too low, because the sea foam would soak the feathers.

[2]

[2] Image taken from `http://en.wikipedia.org/wiki/Daedalus`.

DAIDALUS

Detect and **A**void **A**lerting **L**ogic for **U**nmanned **S**ystems

- DAIDALUS is a reference implementation (Java, C++, and PVS) of a detect and avoid (DAA) concept for Unmanned Aircraft Systems.

- At the core of the DAA concept, there is a mathematical definition of the well-clear concept.

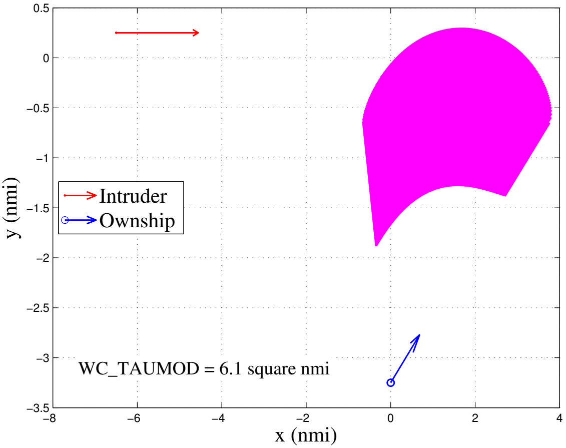
- DAIDALUS provides algorithms for
  - Checking well clear (1×1)
  - Predicting loss of well clear (1×1)
  - Computing alert level (1×1)
  - Computing conflict and recovery bands ($1\times n$)

Well Clear

- Two aircraft are *well clear* if appropriate distance and time variables determined by their states remain outside a set of predefined threshold values.
- A well-clear violation occurs when:
  - range is less than DMOD **or** (distance at time of CPA is less than HMD **and** modified tau is less than TAUMOD) **and**
  - relative altitude is less than ZTHR **or** time to co-altitude is less than TCOA.
- Concrete values for threshold values is matter of research. SARP recommendation: HMD = DMOD = 4000 ft, TAUMOD = 35 s, ZTHR = 450 ft, and TCOA = 0 s.

Well-Clear Violation Volume

Top View of an Example Encounter



Well-Clear Properties

- Inclusion: For an appropriate choice of parameters, the well-clear violation volume is larger than the TCAS volume.
- Symmetry: In a pair-wise situation, both aircraft make the same determination about their well-clear status.
- Local Convexity: In a non-maneuvering trajectory, there is at most one time interval where the aircraft are in well-clear violation.

Well-Clear Algorithms: Time To Violation

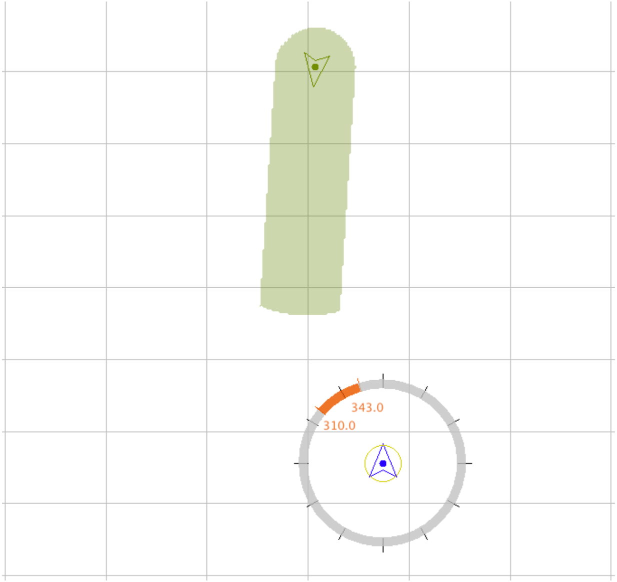
- Given ownship and intruder state information and a lookahead time, return time interval of well-clear violation assuming non-maneuvering trajectories.
- Return empty interval when aircraft are not predicted to be in well-clear violation within the lookahead time.
- Return an interval that contains 0 (current time) when aircraft are currently in well-clear violation.

Well-Clear Algorithms: Conflict Bands

- Given ownship and traffic state information and a lookahead time, compute ranges of *track*, *ground speed*, *vertical speed*, and *altitude* that lead to well-clear violation within lookahead time. . .
- . . . assuming a kinematic trajectory for the ownship and non-maneuvering trajectories for the traffic aircraft.

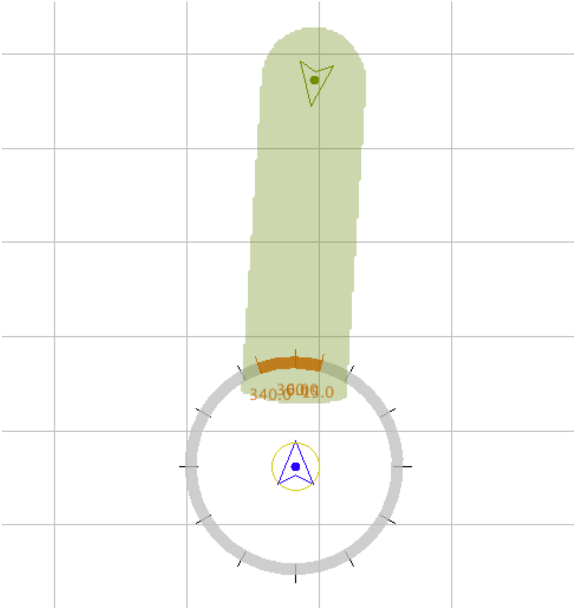
Preventive Bands

Bands outside current trajectory of the aircraft:



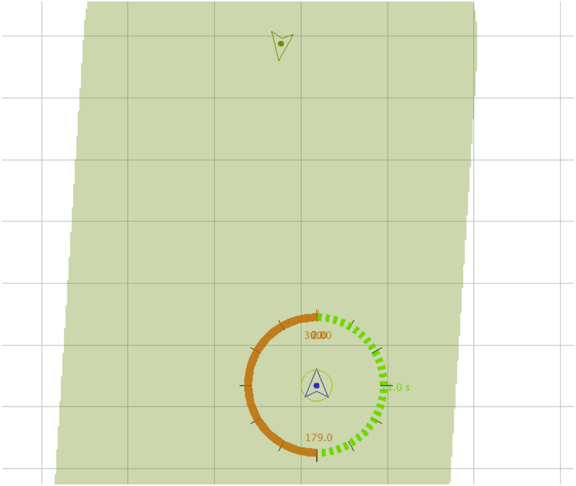
Corrective Bands

Bands in current trajectory of the aircraft:



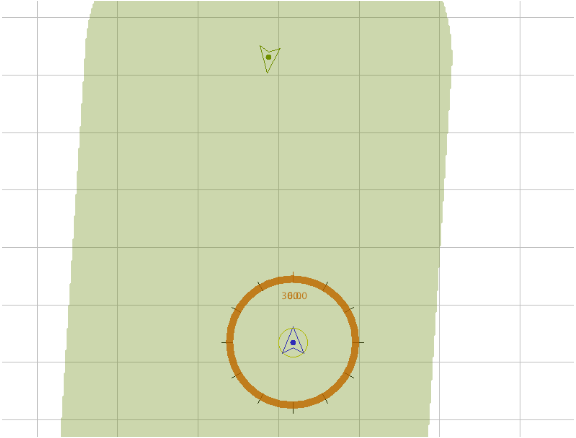
Recovery Bands

Aircraft are (about to be) in well-clear violation:



Full Red

Aircraft are within DMOD and ZTHR distance:



Well-Clear Algorithms: Alerting Logic

- Given ownship and intruder state information, return an alert level (from 0 to 4) indicating severity of potential loss of well clear.
- Two alerting schemas are supported:
  - Thresholds-based.
  - Bands-based.

Thresholds-Based Alerting Logic

- Alert levels correspond to predicted violation with respect to different sets of threshold values. The smaller the values, the greater the severity level.
- Logic: For a given intruder, return most severe alert type for which Time To Violation is less than Alerting Time.

Type	Symbol	Threshold Values[3]	Alerting Time
4		HMD=0.75 nm, ZTHR=450 ft	25 s
3		HMD=0.75 nm, ZTHR=450 ft	75 s
2		HMD=1.0 nm, ZTHR=700 ft	75 s
1		HMD=1.5 nm, ZTHR=1200 ft	85 s
0		–	–

[3] TAUMOD=35 s and TCOA=0 s.

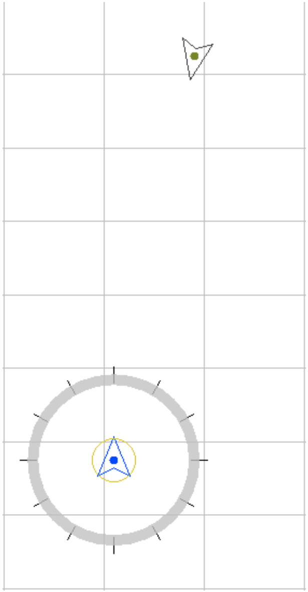
Bands-Based Alerting Logic

- Alert levels correspond to types of bands, i.e., no bands, preventive, corrective, and recovery.
- Logic: For a given intruder, return alert type corresponding to type of bands contributed by that aircraft.

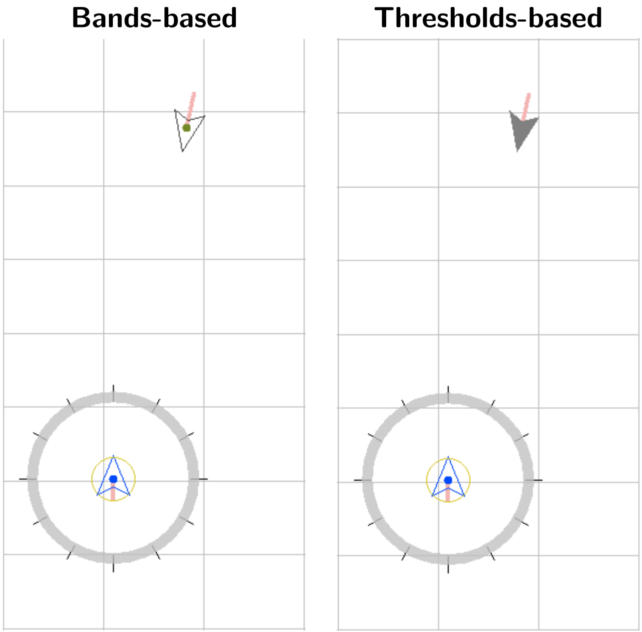
Type	**Symbol**	**Bands**[4]
4		Full Red
3		Recovery
2		Corrective
1		Preventive
0		None

[4] HMD=0.65 nm, ZTHR=450 ft, TAUMOD=35 s. TCOA and Alerting Time are matter of research.

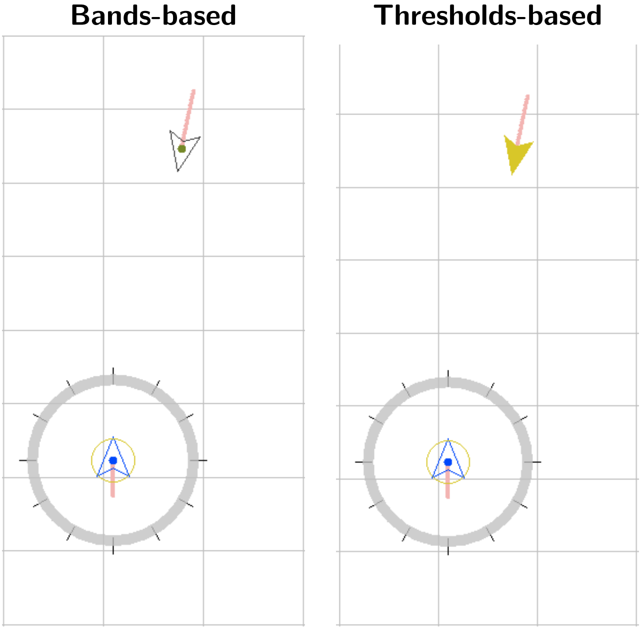
Time 0



Time 20s

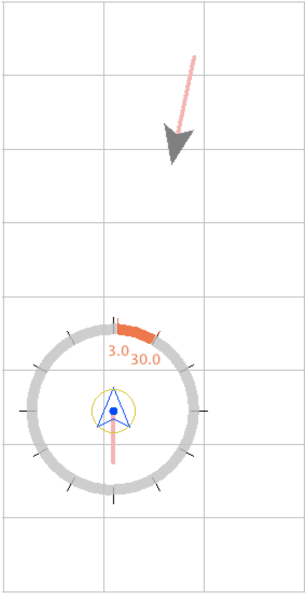


Time 34s

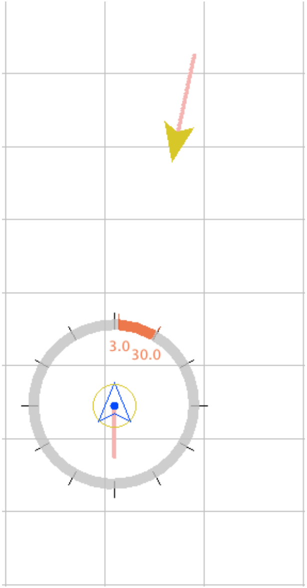


Time 50s

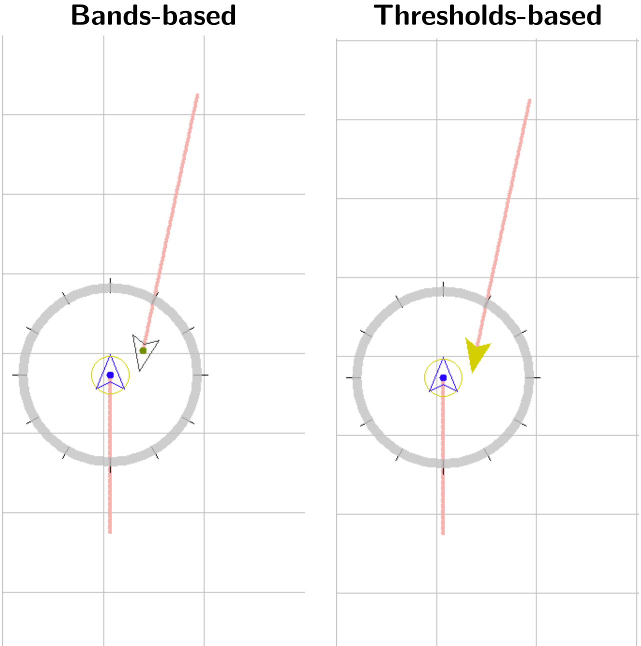
Bands-based



Thresholds-based

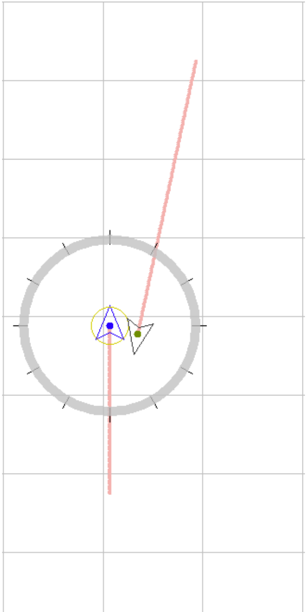


Time 140s

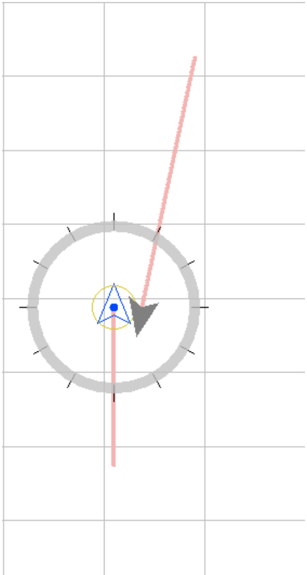


Time 151s

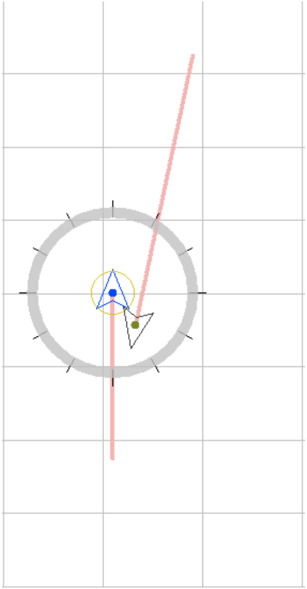
Bands-based



Thresholds-based



Time 160s



Current Status

- Formal specification and verification of algorithms in the Prototype Verification System (PVS): done.
- Prototype code in Java and C++: mostly done.
- Software verification: in progress.

References (I)

- C. Muñoz, A. Narkawicz, G. Hagen, J. Upchurh, A. Dutle and M. Consiglio, *Detect & Avoid Alerting Logic for Unmanned Systems (DAIDALUS)*, submitted 2015.
- J. Upchurch, C. Muñoz, A. Narkawicz, M. Consiglio, and J. Chamberlain, and M. Consiglio, *Characterizing the Effects of a Vertical Time Threshold for a Class of Well-Clear Definitions*, submitted, 2015.
- J. Upchurch, C. Muñoz, A. Narkawicz, J. Chamberlain, and M. Consiglio, *Analysis of Well-Clear Boundary Models for the Integration of UAS in the NAS*, Technical Memorandum, NASA/TM-2014-218280, June 2014.
- C. Muñoz, A. Narkawicz, J. Chamberlain, M. Consiglio, and J. Upchurch, *A Family of Well-Clear Boundary Models for the Integration of UAS in the NAS*, Proceedings of the 14th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, AIAA-2014-2412, Atlanta, Georgia, 2014.

References (II)

- A. Narkawicz, C. Muñoz, J. Upchurch, J. Chamberlain, and M. Consiglio, *A Well-Clear Volume Based on Time to Entry Point*, Technical Memorandum, NASA/TM-2014-218155, January 2014
- C. Muñoz, A. Narkawicz, and J. Chamberlain, *A TCAS-II Resolution Advisory Algorithm*, Proceedings of the AIAA Guidance, Navigation, and Control Conference (GNC), AIAA-2013-4622, Boston, Massachusetts, August 2013.
- M. Consiglio, J. Chamberlain, C. Muñoz, and K. Hoffer, *Concept of integration for UAS operations in the NAS*, Proceedings of the 28th International Congress of the Aeronautical Sciences (ICAS 2012), 2012.

Software Releases Under NASA's Open Source Agreement

- ACCoRD $\subseteq$ Bands $\subseteq$ Chorus $\subseteq$ Stratway: `http://shemesh.larc.nasa.gov/fm/fm-at-codes.html`.
- Well-Clear: `http://github.com/nasa/WellClear`.
- DAIDALUS $\subseteq$ Stratway $\cup$ Well-Clear.